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Ultraviolet radiation drives methane emissions from terrestrial plant pectins

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Summary

- Recent studies demonstrating an *in situ* formation of methane (CH₄) within foliage and separate observations that soil-derived CH₄ can be released from the stems of trees have continued the debate about the role of vegetation in CH₄ emissions to the atmosphere. Here we report a study of the role of ultraviolet (UV) radiation in the formation of CH₄ and other trace gases from plant pectins *in vitro* and from leaves of tobacco *in planta*.
- Plant pectins were investigated for CH₄ production under UV irradiation before and after de-methylesterification and with and without the singlet oxygen scavenger 1,4-diazabicyclo[2.2.2]octane (DABCO). Leaves of tobacco were also investigated under UV irradiation and following leaf infiltration with the singlet oxygen generator rose bengal or the bacterial pathogen *Pseudomonas syringae*.
- Results demonstrated production of CH₄, ethane and ethylene from pectins and from tobacco leaves following all treatments, that methyl-ester groups of pectin are a source of CH₄, and that reactive oxygen species (ROS) arising from environmental stresses have a potential role in mechanisms of CH₄ formation.
- Rates of CH₄ production were lower than those previously reported for intact plants in sunlight but the results clearly show that foliage can emit CH₄ under aerobic conditions.

Key words: methane, pectin, vegetation, reactive oxygen species, *Nicotiana tabacum* (tobacco), ultraviolet (UV) radiation, DABCO.

Introduction

There remains considerable discussion among plant physiologists about recent observations of the production of CH₄ by vegetation foliage under aerobic conditions (Dueck & van der Werf, 2008). Observations by Keppler *et al.* (2006) first demonstrated that dry and live leaf material could produce CH₄, with rates influenced by sunlight and temperature, and this was suggested as a possible explanation for unexpectedly high atmospheric concentrations of CH₄ detected over tropical rainforests (Bergamaschi *et al.*, 2007). Biospheric CH₄ emissions to the atmosphere are thought to originate mostly from anaerobic microbial processes but experimental observations (Keppler *et al.*, 2006; Sanhueza & Donoso, 2006; Wang *et al.*, 2008), atmospheric measurements (Crutzen *et al.*, 2006; do Carmo *et al.*, 2006; Miller *et al.*, 2007) and subsequent analyses (Bousquet *et al.*, 2006; Houweling *et al.*, 2006; Ferretti *et al.*, 2007) do suggest the possibility of a modest CH₄ flux from terrestrial vegetation. Two subsequent investigations were unable to demonstrate CH₄ emissions (Beerling *et al.*, 2007; Dueck *et al.*, 2007) but a recent study, using measurements in the dark, has suggested that some woody plants, but not grasses, may emit small amounts of CH₄ (Wang *et al.*, 2008). The CH₄ was hypothesised to originate from methoxyl groups (Keppler *et al.*, 2006), and recently Keppler *et al.* (2008) have used isotope analysis to demonstrate an influence of temperature and UV radiation on CH₄ emissions from pectin and polygalacturonic acid *in vitro*. The roles of UV radiation and temperature in CH₄ emission from leaves have also been demonstrated by Vigano *et al.* (2008) while observations that CH₄ emissions from vegetation may arise from dissolution of soil CH₄ and its transport above ground in the transpiration stream (Rusch & Rennenberg, 1998; Terazawa *et al.*, 2007) has widened the debate about possible CH₄ sources in vegetation. At present, the mechanisms by which terrestrial

vegetation may emit CH₄ from foliage under aerobic conditions remain to be identified (Schiermeier, 2006, 2007; Dueck & van der Werf, 2008).

The role of temperature and sunlight in the observations of Keppler *et al.* (2006) and the well-known role of UV radiation in photodegradation of plant material (Austin & Vivanco, 2006) led us to investigate the role of UV radiation in CH₄ production from foliage. In earlier experiments, we found that leaf litter from oak trees grown under elevated UV-radiation had an accelerated decomposition rate and reduced extractability of carbohydrates that implied changes to cell wall components (McLeod *et al.*, 2007). Over half of plant primary cell wall dry mass may be comprised of pectins, which are cell-wall polysaccharides rich in α -D-galacturonate residues with variable proportions of methylesterification (Seymour & Knox, 2002). We therefore investigated the release of CH₄ and other gases from pectin-impregnated glass fibre sheets, dried and exposed to UV radiation (from experimental lamps and from sunlight) inside gas-tight UV-transmitting bags filled with ambient air at 30°C. Care was taken in the experimental design to eliminate possible confounding effects from any contamination of the glass fibre or the release of low molecular weight hydrocarbons from the gas bag material. We also examined trace gas production from UV irradiated leaves of the C3 sub-tropical herb *Nicotiana tabacum* L. that were detached in order to limit transpiration as a possible CH₄ source. Sharpatyi (2007) recently suggested that a free-radical process would produce CH₄ from plant polysaccharides under the influence of UV-radiation, which is well-known to produce reactive oxygen species (ROS) in plant tissue (Björn, 2002). We therefore investigated CH₄ production from glass fibre impregnated with pectin and the ROS-scavenger DABCO (Wang *et al.*, 2006) and also from de-methylesterified pectin.

ROS are generated in foliage by a range of environmental stresses including: drought, nutrient deficiency, attempted pathogen infection, high temperature, acidic precipitation and ozone exposure (Apel & Hirt, 2004; Wang *et al.*, 2006). We therefore also compared the effects of UV irradiation on CH₄ production from tobacco leaves with those from leaves infiltrated with water, the singlet oxygen generator rose bengal (Filkowski *et al.*, 2004) or the bacterial pathogen *Pseudomonas syringae* in order to demonstrate the potential role of ROS in CH₄ formation.

Materials and methods

Pectin sheets

Pectin or pectate-impregnated sheets (20.3 x 25.4 cm) were prepared from glass microfibre filters (Whatman GF/A) and commercial pectin derived from citrus fruits (Sigma Chemical Co.). Before use, glass fibre sheets were baked overnight in a furnace at 300°C in order to remove any organic contaminants. Citrus pectin (10 g; Sigma P9135; galacturonic acid content 84%; methoxy content 9.4%; loss on drying 4.1%) was wetted with 20 ml ethanol to form a slurry, which was dispersed in ~950ml deionised water with vigorous shaking. After several hours of stirring until dissolved to form a slightly hazy solution, the volume was adjusted to 1 litre with water. Pectate (de-methylesterified pectin) was prepared by addition of 400 ml of 1% pectin solution to 40 ml of 1.0 M NaOH, and incubation at 20°C for 30 min. Then, with vigorous shaking, sufficient 1 M H₃PO₄ was added to bring the pH to 7.4–7.6. 25 ml of the pectin or pectate solution was then applied to each 20.3 × 25.4 cm sheet of Whatman GF/A glass microfibre filter and allowed to dry in air. With pectin, this resulted in 240 mg of polysaccharide (210 mg galacturonic acid residues) per sheet (equivalent to 23.5 mg (=760 µmol) methyl-ester groups per sheet, giving a theoretical maximum

yield of 12.1 mg CH₄ (~17 ml at STP)). With pectate, there was 175 mg galacturonic acid residue per sheet. Control sheets of glass fibre were prepared in the same way with 25 ml 2% ethanol. Pectin sheets containing DABCO (1,4-diazabicyclo[2.2.2]octane) (Sigma Chemical Co.) were prepared as above except that the pectin solution contained 8 mM DABCO. The absorbance spectrum of a 2.5 g l⁻¹ solution of pectin in distilled water was measured in a scanning spectrometer (Perkin Elmer Lambda 900 UV/VIS/NIR) for evaluation of the UV absorbance of pectin.

Plant growth and leaf infiltration

Tobacco plants (*Nicotiana tabacum* L. cv. Xanthi) were grown from seed in a temperature regulated glasshouse using 7.5 l pots containing a mixture of 75% peat and 25% sand with 750g ground limestone, 1200g ‘Osmocote Exact High K’ slow release fertilizer (NPK 10:11:18 + 2 MgO + trace elements) (The Scotts Company) and 6 g ‘Intercept 60WP’ insecticide (a.i. imidacloprid) (Bayer Environmental Science) per 250 l soil mixture. Day/night temperature was 21/18 °C, light intensity ~150 μmol m⁻² s⁻¹ and daylength extended to 18 h with supplemental sodium lighting. After 8-10 weeks, the youngest fully-expanded leaves were infiltrated on the abaxial surface with a 1 ml syringe with 2 ml of either distilled water, 10 μM rose bengal in water (Sigma Chemical Co.) or a water suspension (0.2 OD₆₀₀) of *PstDC3000(avrB)*. The bacterium was grown in King’s broth (KB) liquid medium (King *et al.*, 1954) supplemented with 50mg l⁻¹ rifampicin and 50mg l⁻¹ kanamycin at 30°C overnight. Bacterial cells were harvested by centrifugation and re-suspended to 0.2 at OD₆₀₀ (the equivalent of 10⁸ cfu ml⁻¹) in 10mM MgCl₂.

Ultraviolet radiation sources

UV radiation was provided by three types of lamp (UV313, UV340, UB351, The Q-Panel Company) filtered with closely-wrapped 125 μm cellulose diacetate, which had a shortwave cutoff at approximately 290 nm (CA lamp filter, Fig. 1b) and so removed ultraviolet-C wavelengths ($<280\text{nm}$). We also used a filter of 0.036 mm UV-opaque polyester (CG lamp filter) ('Courtgard', CPFilms Inc.) to remove UV-B and most UV-A wavelengths ($<380\text{ nm}$). Examples of the spectral irradiance of lamp/filter combinations, including the gas sampling bag, are shown in Fig. 1b. Lamp irradiation was adjusted using a phase-angle dimming system. Experiments performed in natural sunlight took place in the horticultural gardens of the University of Edinburgh at UK National Grid Reference NT 270705 ($55^{\circ} 55' \text{ N}$, $3^{\circ} 10' \text{ W}$), between 6 and 21 September 2006.

Ultraviolet radiation measurements

Ultraviolet spectral irradiance was measured with a double monochromator spectroradiometer (SR991-PC, Macam Photometrics) which was calibrated against tungsten and deuterium lamps traceable to National Physical Laboratory Standards (SR903, Macam Photometrics). During outdoor experiments the solar spectrum was scanned at approximately 15 min intervals and monitored continuously with a broad band UV sensor (Model PMA2102, Solar Light Inc.) that was used to calculate changes in spectral irradiance between scans.

Preparation of sample bags

New 5 l gas sampling bags of 25 μm UV-transparent polyvinylfluoride film (SKC Inc.) were cut open on one side to insert glass fibre sheets and re-sealed using 40 μm

Al adhesive tape. Bags were flushed five times before filling with 250 ml of stock external ambient air. Each pair of sample bags was used for three replicate experiments (which were determined not to have modified UV transmission of the bag material). Experiments using rose bengal, *P. syringae* and UV with tobacco were performed using 200 ml air and a 20 cm square window of 4 mm ‘Sanalux’ glass (Deutsche Spezialglas AG, Delligsen, Germany) attached with Al tape and the remainder of the bag shaded with Al foil. The spectral transmissions of polyvinylfluoride film, Sanalux glass and a range of typical chamber and cuvette construction materials were measured using a scanning spectrometer (Perkin Elmer Lambda 900 UV/VIS/NIR) and are shown in Fig. 1c.

Experimental exposures of pectin and leaves

Experiments on pectin with UV lamps used one sample bag containing one pectin-impregnated glass fibre sheet and another sample bag containing a control glass fibre sheet. Bags were supported on a black butyl rubber sheet (pond liner) on the surface of a thermostatically controlled water bath at 30°C. After two hours, the CH₄ production was determined and then the pectin-impregnated and control sheets were reversed between bags for a further 2-hour exposure. This allowed any difference in CH₄ production from the sample bags themselves to be eliminated from the estimate of CH₄ production from pectins. The CH₄ production inside control bags containing control glass fibre sheets was up to 6.6 ng CH₄ h⁻¹ in sunlight and a maximum of 24.6 ng CH₄ h⁻¹ in lamp experiments at the highest irradiance of UV313 lamps. Outdoor experiments were performed with bags clipped to a temperature-controlled brass plate also covered with black butyl rubber sheet. Temperature was measured inside a sample bag with thermocouples connected to a PC-based control system that adjusted

the temperature of water from a re-circulating water bath. As outdoor UV levels were variable, experiments were conducted for one period of 2 hours without reversing the treatment and control bags. However, the bags were reversed before the next experiment.

Experiments with leaves of *N. tabacum* used one leaf per gas sample bag and were performed inside a growth room at 25-30°C with 18 W m⁻² photosynthetically-active radiation (PAR: 400-700 nm) provided by fluorescent lamps (Philips Master TLD 36W/830) and 3.1 W m⁻² unweighted total UV provided by CA-filtered UV313 lamps (described above). Experiments with PAR and with PAR plus UV radiation were also performed using empty bags as a control and the control gas production was subtracted from treatment values.

Gas concentration measurement

Methane, ethane and ethylene concentrations were determined with a gas chromatograph (Hewlett Packard Series II 5890) equipped with a flame ionisation detector and a column packed with HayeSep Q (80-100 mesh) at 70 °C, with N₂ as carrier gas. Peak integration and autosampling were controlled using a chromatography data system (PeakSimple Model 203). CO₂ was measured with a gas chromatograph (Perkin Elmer 8310) equipped with a thermal conductivity detector, using manual injection. Before and after sample analysis, the gas chromatographs were calibrated using standards of known mixing ratios that spanned the sample values.

Statistical Analysis

Rates of CH₄ production from pectin are reported as the mean of three replicates \pm SE and were analysed by linear regression against UV irradiance values. Trace gas concentrations produced by UV, *P. syringae* and rose bengal treatments of tobacco are also means of three replicates \pm SE and were analysed by individual treatment comparison with the water control using ANOVA with replicate gas bags nested within treatment to achieve a repeated measures analysis (Neter *et al.*, 1996). All statistical tests were performed with the MiniTab statistical package (Version 14.1).

Results and Discussion

The experiments on pectin used fluorescent lamps (filtered to exclude wavelengths <290 nm) in order to provide both UV-B (280-315 nm) and UV-A (315-400 nm) radiation (Fig. 1b) at irradiance levels up to the highest global erythemal UV irradiance (Liley & McKenzie, 2006) (Table 1) and experiments were also conducted in the field with sunlight (Fig. 1b). The absorbance of a 2.5 g l⁻¹ solution of pectin (Fig 1c) demonstrated the presence of UV-absorbing components. Methane production from pectin (Table 1) had an approximately linear relationship to total UV irradiance for each lamp type alone or for sunlight, but considerable scatter when all sources were plotted together. We therefore calculated UV irradiance using a range of idealized (Micheletti *et al.*, 2003) and common spectral weighting functions (Table 1). Straight-line logarithmic weighting functions (e.g. Micheletti *et al.*, 2003) provided significant linear relationships with CH₄ emissions. The best fit was achieved by an idealized function that decayed one decade in 80 nm wavelength (Fig. 1a, inset) giving a significant linear regression between weighted-UV and CH₄ production (Fig. 1a).

These rates of CH₄ production exceed values previously reported for pectin with CH₄-free air inside glass vials (Keppler *et al.*, 2006). Methane production in the dark was undetectable and was reduced to low levels by a UV-opaque filter (Table 1). De-methylesterification of the pectin also reduced CH₄ production to low levels (Fig. 1a).

As free-radical mechanisms could also produce carboxylate radicals and potential dimerisation of methyl radicals, we also examined the production of ethane, ethylene and CO₂, as well as CH₄, from UV irradiation of pectin and found production of all four gases with a molecular ratio of CH₄ : C₂H₄ : C₂H₆ : CO₂ of 1.0 : 0.1 : 0.2 : 240 at a total unweighted UV irradiance of 9.48 W m⁻² (Table 2). UV-induced production of ROS (Björn, 2002) is also a potential free-radical mechanism leading to CH₄ production from the methyl groups of pectins. We therefore examined CH₄ production from pectin-impregnated glass fibre containing the ROS-scavenger DABCO (Wang *et al.*, 2006) and found CH₄ production reduced to low levels (Fig. 1a) thus demonstrating a role of ROS in CH₄ generation from pectins. ROS include hydrogen peroxide (H₂O₂), the superoxide ion (O₂^{•-}) and its non-ionised equivalent the hydroperoxyl radical (HO₂[•]), the hydroxyl radical ([•]OH), and singlet oxygen (¹O₂). Of these five, only [•]OH has been reported to cause extensive oxidative scission of plant polysaccharides (Fry, 1998; Fry *et al.*, 2001). However, DABCO is usually reported as a singlet oxygen scavenger (Wang *et al.*, 2006) thus implicating singlet oxygen in CH₄ generation. More detailed studies using a range of ROS-scavengers are needed to evaluate the precise molecular mechanisms of UV-induced CH₄ formation in this study and those of Keppler *et al.* (2008) and Vigano *et al.* (2008), which reported some CH₄ production from non-methylesterified organic material.

UV-photosensitising compounds (e.g. furocoumarins) are abundant in some plants; therefore ROS formation may be much greater in the foliage of certain plant species than in extracted pectins, although cuticular reflectance of UV and UV-screening compounds (McLeod & Newsham, 1997) will reduce the effective exposure of underlying structures. ROS are generated in foliage by a range of environmental stresses and we therefore also investigated the production of CH₄ from leaves of the C3 sub-tropical herb *Nicotiana tabacum* L. Infiltration of leaves of *N. tabacum* cv. Xanthi with the singlet oxygen generator rose bengal (Filkowski *et al.*, 2004) produced leaf necrosis while infiltration with the bacterial pathogen *Pseudomonas syringae* pv. *tomato* DC3000 carrying the avirulence gene *avrB* (*Pst*DC3000(*avrB*)) (Whalen *et al.*, 1991) resulted in a hypersensitive response (a genetically programmed cell death mechanism (Apel & Hirt, 2004)). All treatments resulted in some CH₄ formation but even greater amounts of ethylene and ethane over the subsequent 45 hours (Fig. 2). Ethane production was only detected after 5 h in all treatments. The amount of CH₄ production was significantly different from the water control for each of the three treatments (repeated measures ANOVA (UV: $F_{1,4}=18.51$, $P=0.013$; *P. syringae*: $F_{1,4}=68.48$, $P=0.001$; rose bengal: $F_{1,4}=11.20$, $P=0.029$) but the mean rate caused by UV irradiation was much greater than other treatments. Methane production caused by the UV treatment, which appeared linear with time over 45 h, was 12.3 ± 3.2 ng g⁻¹ leaf dry weight h⁻¹, which is similar to rates previously reported for detached leaves from a range of species (Keppler *et al.*, 2006) but much smaller than their reported rates for intact plants.

There is a potential for much higher UV-driven emissions at lower latitudes, where all sites between 50°S and 40°N experience peak erythemally-weighted (McKinlay & Diffey, 1987) UV irradiances that exceed 0.25 W m^{-2} (Liley & McKenzie, 2006). Sunlight-driven CH_4 emissions from vegetation were suggested by Keppler *et al.* (2006) as a possible explanation for unexpectedly high atmospheric concentrations of CH_4 detected over tropical regions by satellite remote sensing (Bergamaschi *et al.*, 2007; Schneising *et al.*, 2008). More recent studies have shown that the CH_4 data retrieval was positively biased in tropical regions owing to spectroscopic interference by water vapour, but source inversions based upon an updated data retrieval method still point to substantial tropical CH_4 emissions (Frankenberg *et al.*, 2008).

Converting low latitude erythema irradiances $>0.25 \text{ W m}^{-2}$ using typical spectra derived from a spectral radiation transfer model (Gueymard, 1995, 2001) and using the weighting function for CH_4 production (Figure 1a inset) suggests equivalent values $>11 \text{ W m}^{-2}$ on the CH_4 -weighted irradiance scale of Fig. 1a and $>30 \text{ W m}^{-2}$ CH_4 -weighted UV for the highest global irradiance measured at Cuzco, Peru (Liley & McKenzie, 2006). However, the relationship between appropriately-weighted UV radiation and CH_4 production from plants *in vivo* (and also from dead plant material) should be determined over the full range of global exposure levels before up-scaling to estimates of global emissions as the relationship may not be linear at higher irradiance levels and may not persist through time as the substrate becomes modified. The steep response of the process to shorter wavelengths (Fig. 1a inset) makes it essential to filter experimental lamps to remove wavelengths less than 290nm (McLeod, 1997) in order to ensure realistic exposures in experimental studies.

The use of detached tobacco leaves limited any potential contribution of CH₄ dissolved in the transpiration stream, but raised a question about the effect of leaf detachment on observed gas production. The leaves infiltrated with water served as a control and indicated negligible effect of leaf detachment on gas production, including stress ethylene, during the 45 h experiment. Ethylene is a well-known signal molecule in plants produced by environmental stress (Apel & Hirt, 2004; Wang *et al.*, 2006) and the effect of UV-B irradiation on ethylene production from aminocyclopropane-1-carboxylic acid in tobacco and consequent leaf damage has been reported by Nara & Takeuchi (2002). However, ethylene production directly from UV irradiation of pectins (Table 2) suggests a novel mechanism distinct from the classical ethylene biosynthesis pathways (Wang *et al.*, 2006) which may have implications for ethylene signalling.

These observations in which environmental stresses, particularly from UV irradiation, result in CH₄ emissions from foliage under aerobic conditions may contribute to resolving the mystery of CH₄ sources from terrestrial vegetation in daylight. However, the night time observations of CH₄ (Crutzen *et al.*, 2006) and experimental detection in darkness (Wang *et al.*, 2008) suggest that potential CH₄ sources from the transpiration stream (Terazawa *et al.*, 2007) should also be evaluated further. The rates of CH₄ production induced by rose bengal and *P. syringae* were much lower than those induced by UV irradiation, even though the general oxidative stress caused by these chemical and biological treatments are widespread in the leaf and caused cell death. The trace gas emissions caused by these treatments may originate from different processes (such as lipid oxidation) from those caused by UV irradiation. Nevertheless, the potential effects of ROS generated by other environmental stresses

should be considered. Experimental studies are generally undertaken using plants that have not been subjected to environmental stress or disease and without UV irradiation (e.g. Beerling *et al.*, 2007; Dueck *et al.*, 2007). Another likely reason why studies have failed to report a role of UV radiation in CH₄ production is because materials used in the construction of experimental leaf chambers and cuvettes, such as glass, polymethyl methacrylate (PMMA, 'Perspex' or 'Plexiglas') and polycarbonate do not transmit all UV-wavelengths (Fig. 1c), and plastic polymers may themselves release hydrocarbons under UV-irradiation (Lonneman *et al.*, 1981). The suggestion (Schiermeier, 2006) that some plant species emit up to 4000 times more CH₄ than others may reflect the variability of leaf structures, UV-screening pigments (McLeod & Newsham, 1997), UV-photosensitisers (Björn, 2002) and ROS-scavenging mechanisms (Apel & Hirt, 2004) found in plants. Previous measurements of CH₄ production from vegetation inside glass and 'Plexiglas' chambers (Keppler *et al.*, 2006; Dueck *et al.*, 2007) would have excluded some of the more energetic shorter wavelength UV in solar radiation so that rates of CH₄ emission in the field may be larger than suggested from past experiments. However, reported experimental CH₄ emissions (Keppler *et al.*, 2006; Sanhueza & Donoso, 2006) may also reflect a combination of experimental stress factors that could include heat, desiccation (and UV irradiance) as well as possible artefacts suggested by Kirschbaum *et al.* (2007). Sharpatyi (2007) also implied that gamma radiation is a driver of free radical mechanisms that may lead to CH₄ production and consequently the effect of gamma sterilization of vegetation samples to eliminate microbial effects (e.g. Keppler *et al.*, 2006) should also be tested carefully to ensure that it does not cause biochemical changes that influence subsequent experimental results.

Conclusions

These results provide further evidence that plant pectins can act as a source of CH₄ under aerobic conditions when exposed to UV radiation within the ambient range (280-400nm) from experimental lamps and sunlight. They also provide a first step in understanding the potential mechanisms by demonstrating a role of ROS in CH₄ production and the additional production of ethane, ethylene and CO₂.

The rate of CH₄ production ($\sim 13 \text{ ng g}^{-1} \text{ h}^{-1}$) from tobacco leaves was similar to values reported for detached leaves by Keppler *et al.* (2006), but much lower than their values using intact plants. Nevertheless, vegetation stress factors, especially UV radiation, may have wider implications for biosphere–atmosphere interactions, as any ROS-forming mechanism may have the potential to produce not only CH₄ but also other atmospheric trace gases such as C₂ hydrocarbons and the methyl halides from terrestrial plant sources. A deeper understanding of the biochemical mechanisms for CH₄ production may provide the potential to minimise CH₄ generation from large-scale planting of crops and trees by selection for effective ROS-scavenging and/or UV screening properties. Consequently, the potential of high UV irradiance in the tropics and a range of environmental stress factors to cause ROS formation and trace gas emissions require examination in a range of species, using realistic spectral irradiance and experimental treatments, in order to fully understand the role of these processes in global emissions.

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Table 1 Ultraviolet irradiance and CH₄ production from citrus pectin

Lamp	Ultraviolet irradiance (W m ⁻²)										Methane (ng g ⁻¹ h ⁻¹)	
source/location	Total UV (280-400 nm)	UV-A (315-400 nm)	UV-B (280-315 nm)	ERY ^a	PAS ^b	PGR ^c	QUT ^d	DNA ^e	STN ^f	MET ^h	Mean	s.e.
UV313-CA ^h	0.55	0.36	0.19	<0.01	0.09	0.08	0.12	0.07	0.23	0.30	53.1	4.0
	1.51	1.00	0.51	0.13	0.23	0.22	0.32	0.19	0.64	0.82	109.3	0.6
	2.07	1.37	0.70	0.18	0.32	0.31	0.44	0.26	0.87	1.13	201.2	11.4
	3.69	2.39	1.30	0.34	0.59	0.57	0.82	0.48	1.59	2.04	249.0	11.3
	5.70	3.61	2.09	0.55	0.95	0.92	1.31	0.79	2.52	3.20	361.9	8.2
	8.62	5.74	2.88	0.73	1.27	1.24	1.79	1.01	3.60	4.66	446.6	29.8
	9.48	5.55	3.93	1.10	1.90	1.82	2.53	1.66	4.52	5.62	660.8	36.7
UV340-CA ^h	3.70	3.56	0.14	0.02	0.03	0.10	0.10	0.02	0.60	1.07	143.0	3.8
	10.46	10.08	0.38	0.06	0.08	0.28	0.29	0.04	1.70	3.03	310.0	11.6
	20.35	19.49	0.86	0.13	0.19	0.58	0.64	0.10	3.51	6.13	644.6	29.8
UV351-CA ^h	5.27	5.21	0.06	0.01	<0.01	0.12	0.05	<0.01	0.61	1.26	146.3	6.6

	14.56	14.39	0.17	0.03	0.03	0.33	0.16	0.02	1.72	3.50	296.8	10.2
UV313-CG ⁱ	0.05	0.05	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.02	10.2	1.4
Dark	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.1	1.1
Sunlight	26.51	26.27	0.24	0.04	0.03	0.54	0.25	0.01	2.33	4.98	539.5	-
	7.98	7.88	0.10	0.02	0.01	0.17	0.11	<0.01	0.85	1.71	180.1	-
	22.60	22.40	0.20	0.03	0.03	0.46	0.21	0.01	1.98	4.25	498.3	-
	21.31	21.12	0.19	0.03	0.03	0.43	0.20	<0.01	1.87	4.01	448.5	-
	19.07	18.91	0.16	0.03	0.02	0.39	0.17	<0.01	1.67	3.58	391.4	-
Cuzco, Peru ^j	-	-	-	0.63	-	-	-	-	-	-	-	-

Values of CH₄ production are the mean of three replicate measurements for lamp sources and individual measurements in sunlight (see Methods).

^a ERY: UV (280-400nm) weighted with the Commission Internationale de l'Eclairage (CIE) erythral action spectrum(McKinlay & Diffey, 1987).

^b PAS: UV (280-400nm) weighted with a mathematical formulation (Green *et al.*, 1974) of the general plant action spectrum (Caldwell, 1971).

- ^c PGR: UV (280-400nm) weighted with a new plant growth function (Flint & Caldwell, 2003).
- ^d QUT: UV (280-400nm) weighted with the pyridine dimer action spectrum (Quaite *et al.*, 1992).
- ^e DNA: UV (280-400nm) weighted with the DNA damage action spectrum (Setlow, 1974).
- ^f STN: UV (280-400nm) weighted with the plant growth inhibition function (Steinmuller, 1986).
- ^g MET: Idealized spectral weighting function for CH₄ production that decays one decade in 80 nm.
- ^h Lamps filtered with 125 µm cellulose diacetate which filters UV wavelengths <280 nm (see Fig 1b).
- ⁱ UV313 lamps filtered with 'Courtgard' polyester which filters UV wavelengths <380 nm (see Fig 1b).
- ^j Highest estimated global erythemal irradiation at Cuzco, Peru calculated from the UV index (Liley & McKenzie, 2006).

Table 2 Production of trace gases from ultraviolet irradiation of citrus pectin

Methane (ng g ⁻¹ h ⁻¹)		Ethane (ng g ⁻¹ h ⁻¹)		Ethylene (ng g ⁻¹ h ⁻¹)		CO ₂ (µg g ⁻¹ h ⁻¹)	
Mean	s.e.	Mean	s.e.	Mean	s.e.	Mean	s.e.
660.8	36.7	125.2	14.1	271.0	9.5	433.4	3.6

Values are the mean of three replicate experiments. Total UV irradiance was 9.48 W m⁻² (280-400 nm) with corresponding weighted irradiance values using a range of common spectral weighting functions shown in Table 1.

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Figure 1. Methane production from citrus pectin. (a) Linear regression of CH₄ production with ultraviolet irradiance weighted with the inset spectral weighting function, using cellulose diacetate (CA) filtered lamps: UV313 (●), UV340 (◆), UV351 (◇), UV-opaque ‘Courtgard’ (CG) polyester-filtered UV313 lamps (★) and sunlight (▼). Open symbols correspond to spectra in Fig. 1b. For lamp sources, values are means of three replicates and standard errors are less than symbol size except where visible. For sunlight, values are individual measurements. Other symbols (close to the horizontal axis) show CH₄ production from pectin plus the ROS-scavenger DABCO (▲) and from de-methylesterified pectin (■). Temperature was 30 °C; (b) Spectra of sunlight (SUN) and CA-filtered lamps (UV313, UV340, UV351) and CG-filtered UV313 lamp (CG313) used in experiments; (c) Transmission spectra (solid lines) of filters used in experiments (CA, cellulose diacetate; CG, ‘Courtgard’ UV-opaque polyester) and of materials commonly used to construct experimental plant chambers (GL, 4 mm window glass; PE, 3.8 mm ‘Perspex’; PO, 2.7 mm polycarbonate, SA, 4mm ‘Sanalux’ glass). Absorbance spectrum (right-hand axis) of 2.5 g l⁻¹ pectin (PC) in water (hatched line).

Figure 2. Trace gas production from tobacco (*Nicotiana tabacum* var. Xanthi). (a) Methane; (b) Ethane; (c) Ethylene. Leaves were infiltrated with 2 ml of either water (○), a *PstDC3000(avrB)* suspension (□), a 10 μM rose bengal solution (●) or water plus UV irradiation (■). All treatments were under 18 W m⁻² (87 μmol m⁻² s⁻¹) PAR (400-700 nm). The UV irradiation treatment was 3.14 W m⁻² (280-399 nm) (equivalent to 1.47 W m⁻² UV_{CH₄} – see Fig. 1a) and temperature was 25-30 °C. Values are means of three replicates and standard errors are smaller than the symbol except where visible.

FIGURE 1

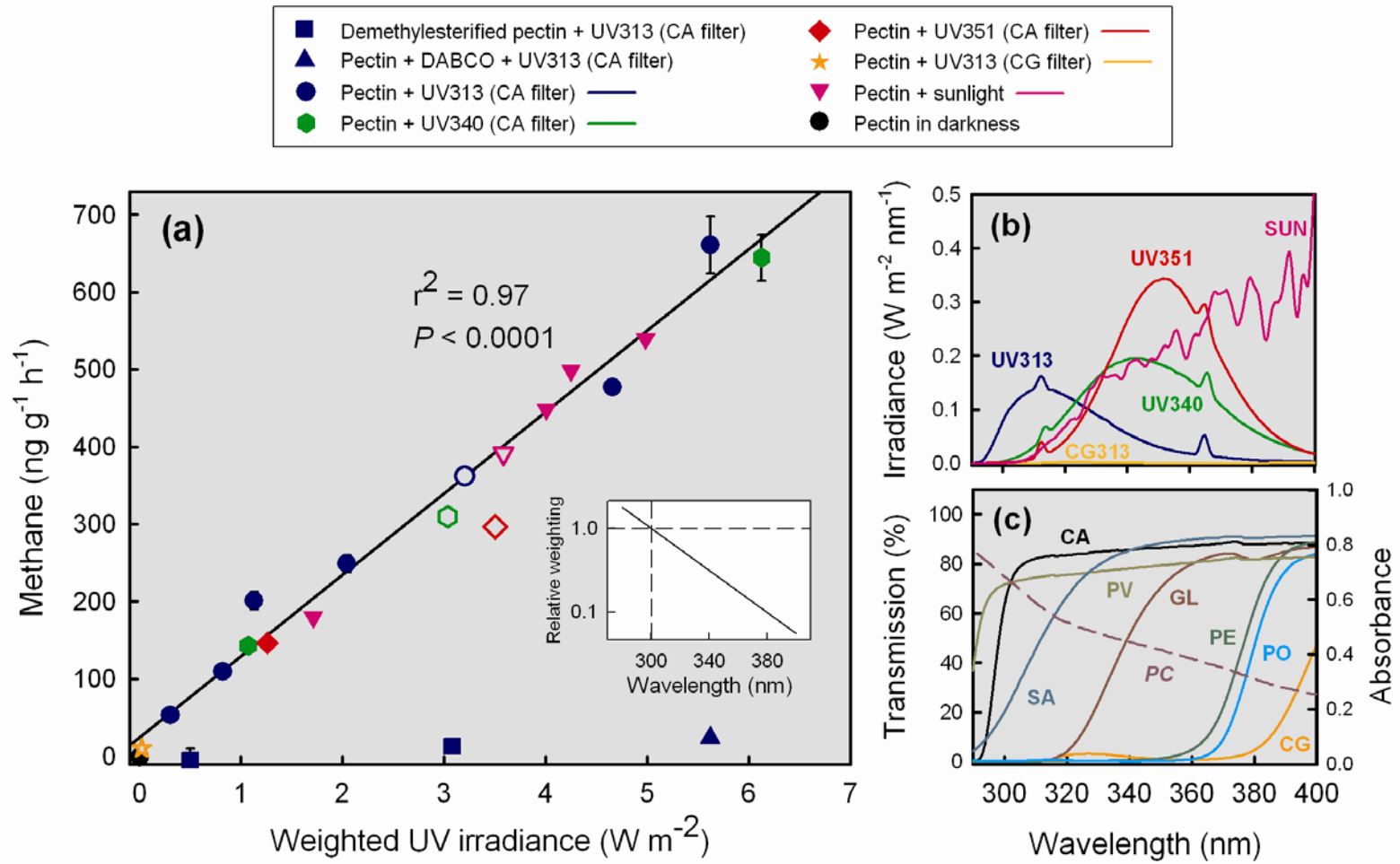


FIGURE 2

